Project Summary

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The Influence of Short Polymeric Fibers on Crack Development in Clays

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Purpose: To evaluate a methodology for preventing crack development in clays due to desiccation by the use of short polymeric fibers.

Reference: "Effects of Short Polymeric Fibers on Crack Development in Clays." Stacy Shulley, Dov Leshchinsky, and Hoe I. Ling. University of Delaware. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, Sep 1997. Technical Report REMR-GT-122.

Impact: The inclusion of randomly distributed, discrete tensile reinforcement elements in compacted clay offers a potential solution to the problem of sloughing instability of levees. Such elements are available as short polypropylene fibers. An investigation was conducted to assess the feasibility of using these fibers to reduce the desiccation cracking and to increase the strength of compacted clay. Based on the findings obtained from the investigation, there is potential for the use of fiber reinforcing in clays. However, the effectiveness of the fibers in strengthening the soil and reducing desiccation cracking is limited by the mechanisms by which the fibers interact with the soil. It is suggested that the reinforcing fiber concept might be improved if longer fibers with a different texture or surface coating were used.

Background: Many earth structures such as levees and highway embankments are constructed of clayey soils. As the plasticity of the clay increases, cracks tend to develop during cycles of long dry spells. During periods of rainfall that follow the dry spells, water fills the cracks and fissures. In addition to increasing the hydrostatic forces, the water is slowly absorbed by the clay. The effect of the absorbed water is to increase the unit weight of the clay as well as to decrease its shear strength. These mechanisms result in a simultaneous increase of the sliding (driving) forces and decrease of the resisting (shear strength) forces. This shrink / swell behavior also results in deepening of the cracked clay zone which may eventually reach a depth of 9 ft or more, especially for clays with a plasticity index greater than 40. Furthermore, the seasonal shrinking and swelling behavior of the cracked clay zone results in a progressive reduction of the shear strength of the clay, perhaps approaching its residual strength. Although the structure may have been designed with a sufficient factor of safety against rotational failure, the increased driving forces coupled with the decrease of shear strength of the clay in the cracked zone results in a decrease of the factor of safety against shallow failures, as evident by the sloughing slides that frequently occur in conjunction with a heavy rainfall. One possible solution to the problem of surficial slides involves the inclusion of randomly distributed tensile reinforcement elements to reduce the development of desiccation cracks in the clay.

Experimental Investigation:

Objectives. The primary objective of this investigation was to assess whether the inclusion of discrete tensile elements, specifically polypropylene fibers, could reduce the desiccation cracking and increase the strength of clays. Secondary objectives included:

1. The effects of fiber inclusion on the development of cracks as a function of
   * the plasticity index of the soil
   * the number of cycles of wetting and drying

2. The effects of fibers
   * in reducing the volume change associated with shrink / swell
   * on the unconfined strength of the soil
   * on the tensile strength of the soil

3. The effectiveness of fibers in reducing clay surface disintegration due to water erosion

4. The optimal fiber content in terms of
   * workability
   * compaction
   * strength
   * effectiveness in reducing desiccation cracking

5. The effectiveness of the fiber structure

Soils. To assess the potential use of polypropylene fibers over a range of clay soil plasticities, i.e., many different types of clays, tests were conducted on laboratory-prepared clay soils as well as naturally-occurring clay soils.

Laboratory-Prepared Clays. Soils with a wide range of plasticity were prepared in the laboratory by mixing different proportions of kaolinite, calcium bentonite and sodium bentonite.

For each mixture, the amount of sodium bentonite and calcium bentonite, by weight of the total mixture, was varied while the amount of kaolinite was held constant at 15 percent. It was determined experimentally that a kaolinite - calcium bentonite mixture produced soils with a plasticity index (PI) ranging from 25 to 60, whereas soils with a PI ranging from 60 to 100 were prepared by mixing kaolinite, calcium bentonite and sodium bentonite.

Ten mixtures that provided PI's ranging from 25 to 100 were chosen. This range of plasticity indices was selected because it was believed to be realistic for clays encountered in the field. Table 1 shows the mixture proportions for soils with the desired plasticity indices. The experimentally determined maximum dry density and optimum moisture content for each soil is also tabulated. The Atterberg Limits for each mixture were determined according to ASTM D4318. The maximum dry density and the optimum moisture content for each mixture were determined according to ASTM D698.

<u>Natural Clays.</u> To verify the relevance of the data obtained using the laboratory prepared soils, four natural clay soils were also tested. The soils were identified as Yazoo (CH) clay from Jackson, Mississippi; Silver Creek (CL) clay from Fort Worth, Texas; Dallas 1 (CH) clay from Dallas, Texas; and Dallas 2 (MH) "clay" from Dallas, Texas. The Atterberg limits, maximum dry densities, and optimum moisture contents for each soil were determined according to appropriate ASTM procedures. These data are presented in Table 2.

Polypropylene Fibers. Discrete, fibrillated, polypropylene fiber bundles used for the investigation were manufactured such that when stretched perpendicular to the direction of the long chain polymer, a miniature mesh with a diamond shaped pattern was formed. Conceptually, the fibers would spread open and disperse into net, grid, or fiber configurations when mixed with the soil. The fiber bundles were nominally 1.0-inch long, 0.1-inch wide and approximately 0.01-inch thick. Each bundle consisted of 7 to 10 interconnected fibers; each fiber was approximately 1-inch long by 0.035-inch wide. The fibers were inert and resistant to ultraviolet degradation. The engineering properties of the fibers were: specific gravity = 0.9, tensile strength = 45,000 psi, tensile elongation = 15 percent, and Young's modulus = 700,000 psi.

Sample Preparation. For the laboratory-prepared soils, the proportions of kaolinite and calcium bentonite and/or sodium bentonite were weighed and thoroughly mixed. For the natural soils, an appropriate amount of the soil was pulverized and put through a No.10 sieve. Then, either the natural or laboratory-prepared soil was gradually mixed with distilled water to bring its water content to about 2 percent above the optimum water content. Fibers were weighed and mixed into the wet soil. Most specimens were molded with fiber contents of 0%, 0.1% or 0.3% by dry weight of the soil, although a few specimens were molded with a fiber content of 1.0%.

Initially, the hand mixing procedure was used. However, it was difficult to get the opened fibers distributed uniformly throughout the soil because they tended to open slightly and then clump together. A second mixing procedure which involved the use of a mechanical mixer to blend the soil was then used. The fiber-soil mixture obtained from the mechanical-mixing method was much more uniform than the mixture obtained by the hand-mixing method. After mixing was completed, the mixture was covered with a plastic wrap and allowed to cure for 24 hours. This curing process produced a more even distribution of moisture throughout the soil.

Volume Change / Cracking Test. The volume change / cracking test was used to assess the effects of fiber inclusion on the development of cracks. Specimens were formed by compacting soil into a standard Proctor mold (4-in.-dia. by 4.58-in. high) to 95% of maximum dry density. All compaction was done with a motorized rammer using three approximately equal lifts. After compaction, the specimens were subjected to a series of drying and wetting cycles to assess the development of cracks. Each series consisted of testing four replicate specimens. The first specimen was used for reference purposes. After the specimen was compacted, it was extruded from the mold and placed in an oven at 120°F (48.9°C) for a period of 24 hours. At the end of 24 hours, the specimen was removed from the oven and measured for volume change and cracking. The second specimen was prepared in the same manner as the first specimen. However, the second specimen was not extruded from the mold prior to drying in the oven as the mold was needed to keep the specimen from disintegrating in the water during a soaking phase(s) that followed the drying cycle(s).

At the end of 24 hours, the specimen (and mold) was removed from the oven and submerged in distilled water. After 24 hours of soaking, the specimen was removed from the water, extruded from the mold, and placed in the oven for a second drying cycle. After 24 hours, it was removed from the oven and cracking and volume change measurements were made. Similarly, third and fourth specimens were subjected to one and two each, respectively, additional cycles of drying and wetting, as described for the second specimen. Prior to the beginning of the last drying cycle, each specimen was extruded from the mold. At the end of the last drying cycle, cracking and volume change measurements were obtained.

Two types of data were collected. Volume change data, i.e., height (and diameter after the specimen was extruded) measurements were recorded at the end of each drying and wetting cycle. Surface cracking that had occurred by the end of the last drying cycle was also recorded. The lengths and widths of the cracks were measured on the cylindrical face of the specimen. The maximum crack width and the average crack width were also noted.

The test results indicated that the inclusion of fibers had no consistent effect on the shrink / swell characteristics of either the laboratory-prepared or the natural clay soils. For most of the laboratory-prepared clays, the volumetric strain was on the order of 11 +/- 8 percent for specimens with plasticity indices greater than 40. The data obtained from tests on natural clay soils provided results similar to those obtained using the laboratory-prepared soils. The only significant difference was that the natural soils, for some cases, showed a net increase, instead of a net decrease, in volume.

Unconfined Compression Test. The unconfined compression test was used to assess influence of fibers on the strength and deformation characteristics of the soil. Specimens were compacted into a standard Proctor mold to 95% of maximum dry density. After the soil was compacted, a brass sampling tube was pressed into the soil contained within the mold to obtain specimens with appropriate height to diameter ratios for unconfined compression tests.

Two specimen sizes, 1.85-in.-dia. by 4.58-in. high and 2.9-in.-dia. by 6.5-in. high, were selected to investigate the influence of the ratio of fiber length to specimen dimensions on strength data. After each specimen was extracted from the sampling tube, it was wrapped in plastic to prevent drying until it was tested. The unconfined compression tests were conducted using a controlled rate of strain of two percent of the initial height of the specimen per minute. Deflection and load data were collected during each test.

Problems arose when sampling from the compacted soil. When pushing the sampling tube into the soil containing fibers, the fibers along the advancing edge of the sampling tube were dragged through the soil. After extraction, the specimen would sometimes have voids and striations along the sides where the fibers had been pulled out. Periodically, the specimens would break during extraction from the sampling tube. Occasionally, the sampling tube would not enter the compacted soil straight resulting in a specimen in which the ends were not perpendicular to the axis of the specimen.

The results of the tests indicated that the strengths of clays containing fibers were generally about 10- to 15 percent less than the strengths of clays that did not contain fibers. It was believed that the decrease in strength was related to disturbance of the specimens containing fibers that occurred during the sampling and extrusion process. It was concluded that the fibers had no apparent effect on the unconfined strength of the clay. However, this conclusion was based upon very limited test data obtained on specimens for which the quality was suspect.

Tension Test. The tensile test was also selected to assess influence of fibers on the strength and deformation characteristics of the soil. Specimens were molded into the shape of a rectangular bar with a reduced cross-section near its center. The reduced section isolated a zone in which failure would occur, as opposed to the ends of the bar which were gripped by the tensile loading apparatus. The tensile test apparatus used for this investigation was a modification of the device used by Peters and Leavell (1988).

Each specimen was compacted to approximately 95% of maximum dry density using three lifts. To prepare each specimen, an appropriate amount of soil was weighed, placed in the rectangular mold, and spread to a uniform thickness. A plate that fit inside the mold was placed on the top of the soil and tamped to the desired height (thickness of the lift of soil). After the specimen was molded, it was covered with a plastic wrap and cured for 24 hours to allow redistribution of moisture.

To conduct the test, the mold containing the specimen was placed in the direct shear machine. The side pieces on the mold were removed which allowed the ends of the specimen to be pulled, thereby inducing a tensile load on the specimen. The tension tests were conducted at a displacement rate of 0.015 inches per minute. Load and displacement were recorded.

A major problem encountered during the testing of the tensile specimens was that they tended to rotate during the test. This rotation caused a tensile as well as a torsional load to be applied to the specimen. After assessing the problem, it was determined that rotation of the specimen could not be prevented without fabricating a new device. Therefore, the recommendations regarding the influence of fibers on the tensile strength of the clays were based upon a few tests for which very little or no rotation occurred during the test.

Due to the limitations of the testing methods, tension tests were not performed on specimens that had undergone wet /dry cycling. The results discussed herein only represent the effect of the fibers on clay that had not undergone desiccation cracking. Although it cannot be quantified with great confidence, the inclusion of fibers increased the tensile strength of the clay specimens and affected the type of failure. Specimens without fibers reached a peak strength and then dropped to zero as the specimen cracked, whereas specimens containing fibers reached a slightly higher peak strength and then gradually lost strength as the fibers were pulled out of the soil. It was also observed that the machine-mixed samples had a slightly higher tensile strength than the hand-mixed samples.

Spin Test. The spin test (Richter, 1992) was selected to assess the effectiveness of fibers in reducing clay surface disintegration due to surface runoff erosive forces. Specimens were molded to 95% of maximum dry density in a standard Proctor mold. After compaction, the specimen was extracted from the mold and weighed, and then clamped to a shaft attached to an electric motor and submerged in a tank filled with water. To conduct the spinning test, the submerged specimen is rotated about its axis at a constant rotational velocity for a measured time increment. At the end of the spinning time, the portion of the specimen remaining intact was lifted out of the water, removed from the clamping mechanism, weighed, and then placed in the oven to dry. Spinning times of 5, 10, 15 and 20 minutes were selected. The spinning velocity which was chosen to simulate surface runoff (i.e., the relative velocity between water and the surface of the specimen) was one ft/sec relative tangential velocity (53 rotations per minute).

It should be noted, however, that the spin test exaggerates the erosive forces on the surface of the soil specimen, as the specimen is subjected to centrifugal forces as well as shear forces due to water drag. For this investigation, the outward acceleration generated by the spinning was about 6 ft/sec^2, as compared to gravity which is 32.2 ft/sec^2. Because of the limitations, the spin test should be considered only as an index test with its value limited to a comparison of clays molded with and without fibers.

For this investigation, the inclusion of distinct fibers did not yield a consistent effect on the amount of soil that disintegrated due to water erosion. For the laboratory-prepared soils, the spin tests showed that the inclusion of fibers had very little effect. For the natural soils, the inclusion of fibers led to a slight decrease in the amount of soil eroded for the Silver Creek and Dallas 1 specimens, but no effect for the Dallas 2 specimen. It should be noted however, that there are numerous variables such as type and amount of cations, composition of soil (percentage of sand, silt, clay), type and amount of clay minerals (kaolinite, illite, montmorillonite) which could influence the erodibility of a soil (Perry 1975).

Optimal Fiber Content. Based on the results obtained during this investigation, the optimal fiber content was 0.3% of the dry weight of the soil. This concentration of fibers provided the best combination of workability, increase in tensile strength, and effectiveness in reducing the amount of desiccation cracking.

Effectiveness of the Fiber Structure. The effectiveness of fibers in strengthening the soil and reducing desiccation cracking is limited by the mechanisms by which each fiber interacts with the soil. The mechanism by which the fibrillated fibers interact with the soil at low normal stresses is purely adhesion. Because the surface area of fibers intersecting a potential crack is quite small, little tensile force is needed to overcome the adhesion and pull the fiber out of the soil.

To increase the adhesion of the soil to the fibers, the surface roughness or the surface area of each fiber needed to be increased, i.e., wider or longer fibers. However, such fibers were not available. An alternative method to improve the interaction between the fibers and the soil was to use fibers connected by cross pieces, such as a grid. To test this hypothesis, a small grid-like fiber was created using a fine mesh fiberglass window screening material. The screen was cut into pieces 1-in. long by 0.20-in. wide. At this width, each “mesh fiber” had three to four longitudinal fibers connected by 16- to 17 cross pieces. These fibers were used for a series of cracking / volume change tests and tension tests. All screen fiber tests were conducted with a machine-mixed laboratory-prepared soil with a plasticity index of 60.

The results of the cracking tests showed that both the percent cracking and the average crack width were less with the incluslon of screen fibers than with fibrillated fibers. The tensile strength of the soil with screen fibers was comparable to the strength of the soil with fibrillated fibers. It was concluded that screen fibers were more effective at decreasing the desiccation cracking of clay than fibrillated fibers were. This observation inferred that the design of the fibers could be modified and optimized to better interact with clay soils.

Summary. It was concluded that there was some potential for use of fibers in clays. The results demonstrated that the fibers were effective in reducing the amount of desiccation cracking that occurred in clays. However, when the clay soils were subjected to wet/dry cycles, the effectiveness of the fibers is not as evident. The inclusion of fibers also increased the tensile strengths of the clay soils and provided a more ductile behavior that was not present in the specimens without fibers. The results showed that fibers had no effect in reducing clay surface disintegration due to water erosion and a negligible effect on the unconfined strength of the treated clay as compared to the untreated clays.

It was also demonstrated through the use of grid-like “mesh fibers” that the effectiveness of the fibers in strengthening the soil and reducing desiccation cracking was limited by the mechanisms by which the fibers interact with the soil. The “mesh fibers” were more effective at reducing the cracking and increasing the tensile strength of the clay than were the fibrillated fibers. It was suggested that longer fibers with a different texture or surface coating could provide better adhesion between the fiber and the soil and thus increase the tensile resistance required to pull the fiber out of the soil.

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Table 1. Atterberg Limits, Maximum Dry Density, Optimum Water Content, Mixture Proportions for Laboratory-Prepared Clays

Atterberg Limits			Maximum	Optimum	Percent by Weight		
Plasticity Index %	Liquid Limit %	Plastic Limit %	Dry Density pcf	Water Content %	Calcium Kaolinite %	Sodium Bentonite %	Bentonite %
24	56	32	-----	-----	100	0	0
61	103	42	-----	-----	0	100	0
390	433	43	-----	-----	0	0	100
25	58	33	88.5	29.0	80	20	0
30	64	34	85.9	30.0	69	31	0
35	70	35	84.7	35.0	58	42	0
40	77	37	81.5	36.0	46	54	0
50	89	39	77.0	39.0	23	77	0
60	102	42	74.5	36.0	15	77	8
70	110	40	73.8	35.0	15	71	14
80	119	39	73.2	37.0	15	67	18
90	130	40	73.2	40.0	15	63	22
100	140	40	72.6	41.0	15	61	24

Table 2. Atterberg Limits, Maximum Dry Density, and Optimum Water Content of Natural Clays

Soil	Plasticity Index %	Liquid Limit %	Plastic Limit %	Maximum Dry Density pcf	Optimum Water Content %
Yazoo	60	86	26	89.1	26.0
Silver Creek	16	33	17	113.9	14.0
Dallas 1	49	71	22	99.9	14.5
Dallas 2	27	62	35	87.8	30.0